

STELLAR CONTENT AND RECENT STAR FORMATION HISTORY OF THE LOCAL GROUP DWARF IRREGULAR GALAXY IC1613¹

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ABSTRACT

We present resolved-star *VI* photometry of the Local Group dwarf irregular galaxy IC1613 reaching $I \sim 23.5$, obtained with the wide-field camera at the 2.5 m Isaac Newton Telescope. A fit to the stellar density distribution shows an exponential profile of scale length 2.9 ± 0.1 and gives a central surface brightness $\mu_{V,0} = 22.7 \pm 0.6$. The significant number of red giant branch (RGB) stars present in the outer part of our images ($r > 16.5$) indicates that the galaxy is actually more extended than previously estimated. A comparison of the color-magnitude diagrams (CMDs) as a function of galactocentric distance shows a clear gradient in the age of its population, the scale length increasing with age, while we find no evidence of a metallicity gradient from the width of the RGB. We present quantitative results of the recent star formation history from a synthetic CMD analysis using IAC-STAR. We find a mean star formation rate of $(1.6 \pm 0.8) \times 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ in the central $r \lesssim 2.5$ for the last 300 Myr.

Subject headings: galaxies: dwarf — galaxies: individual (IC1613) — galaxies: irregular — galaxies: stellar content — galaxies: structure — Local Group

1. INTRODUCTION

IC1613 is a typical dwarf irregular galaxy concerning its luminosity, metallicity and star formation rate (SFR). In fact, it serves as the prototype for the DDO type Ir V. It is a low surface-brightness galaxy with a moderate luminosity ($M_V = -15.3$, van den Bergh 2000) located 730 ± 20 kpc from our Sun. This distance corresponds to a distance modulus $(m - M)_0 = 24.31 \pm 0.06$ (Dolphin et al. 2001) and a scale of 3.54 pc per arcsecond. The recent calculation of Pietrzyński et al. (2006) from near-IR photometry of cepheids gives $(m - M)_0 = 24.291 \pm 0.035$, for which the authors claim a total uncertainty of less than 3%. While the spatial extent estimate of Ables (1972) gives an optical size of $16' \times 20'$, the observation of carbon stars up to $15'$ from the center by Albert et al. (2000) indicate that it is virtually twice that size. Its high galactic latitude, in the southern hemisphere, confers it low extinction and color excess. Here we adopt a reddening of $E(B - V) = 0.02 \pm 0.02$ from Cole et al. (1999).

The H II region metallicity of IC1613 was measured by Talent (1980, see Skillman et al. 1989) to be $12 + \log(\text{O}/\text{H}) = 7.86$ from spectrophotometric observations of the $[\text{O III}]\lambda 4363$ line, while Lee et al. (2003) found $12 + \log(\text{O}/\text{H}) = 7.62$. This corresponds to $[\text{Fe}/\text{H}] = -0.8$ and $[\text{Fe}/\text{H}] = -1.07$ dex respectively (Skillman et al. 2003, hereinafter S03). The mean color $(V - I)_{-3.5}$ of the RGB at $M_I = -3.5$ gives $[\text{Fe}/\text{H}] = -1.3$ for the old and intermediate-age population (Lee et al. 1993). This low overall metallicity and the high gas con-

tent (Hoffman et al. 1996) suggest a primitive state in its evolution.

The star formation history (SFH) has been studied quite extensively by S03 for an HST/WFPC2 field located 7.4 kpc southwest from the center. Their conclusion is a relatively constant SFR over a long period, with the oldest population being more than 10 Gyr old. They also summarize the results about structure and stellar content of the whole galaxy from the literature. More recently, Borissova et al. (2004) analyzed 60 OB associations, apparently correlated with H II regions studied kinematically by Lozinskaya et al. (2003, see also Silich et al. 2006). Magrini et al. (2005) announced the detection of two candidate planetary nebulae.

In this paper we describe a wide-field survey of IC1613: an overview of the observations and data reduction is presented in section 2, and the resulting color-magnitude diagram (CMD) is described in §3. In §4 we examine the extent and morphology of the galaxy, as well as the spatial structure of the different populations in the CMDs. An analysis of the recent SFH at different galactocentric radii is given in §5. Finally, in §6 we summarize the results and present our conclusions.

2. OBSERVATIONS & DATA REDUCTION

Observations of IC1613 in Harris *V* and Sloan Gunn *i'* were conducted on 5 nights between November 1999 and September 2000 using the Wide Field Camera (WFC) at the 2.5 m Isaac Newton Telescope (INT) of the Observatorio del Roque de los Muchachos. The WFC is a mosaic camera made up of four 2048×4096 CCDs, with a pixel size of $0.33''$. The total field of view is about $34' \times 34'$, covering most of the galaxy. The total integration times in *V* and *i'* were 3660 and 1830 seconds, respectively. A detailed observing log is presented in Table 1.

Overscan trimming, bias subtraction and flat-field corrections were performed using the standard routines in

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¹ Based on observations made with the Isaac Newton Telescope operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

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TABLE 1
JOURNAL OF OBSERVATIONS.

UTC Date	Time (UT)	Filter	Exp. Time (s)	Air Mass
1999 Nov 06	22:23	V	60	1.14
1999 Nov 06	22:32	V	1200	1.13
1999 Nov 06	22:53	V	1200	1.12
1999 Nov 06	23:14	V	1200	1.12
2000 Aug 10	04:38	I	30	1.12
2000 Aug 10	04:41	I	600	1.12
2000 Aug 10	04:54	I	600	1.12
2000 Aug 10	05:05	I	600	1.12

IRAF³. The i' images have also been corrected for fringing effects. The DAOPHOT-II/ALLSTAR and ALLFRAME programs (Stetson 1987, 1994) were then used to obtain the instrumental photometry of the resolved stars from the four individual images in each band and for each chip. The ~ 200 stars used to model the point-spread functions (PSFs) were carefully selected to cover the whole field of view and sample the spatial variations of the PSF. The input list of stars for ALLFRAME was created with DAOMASTER from the ALLSTAR photometry files of the individual images. This list contains all the stars that were detected on at least one image. The stars with good photometry were selected among the detected objects using ALLFRAME's fitting parameters σ , χ^2 and *SHARP*. Only those ~ 30000 objects with very good photometry, i.e., with $\sigma \leq 0.15$, $\chi^2 \leq 1.1$ and $-0.3 \leq \text{SHARP} \leq 0.3$, were kept.

Our photometry of chips 1, 3 and 4 of the WFC⁴ was calibrated to standard magnitudes using OGLE's photometry of the same field, kindly provided by Dr. A.

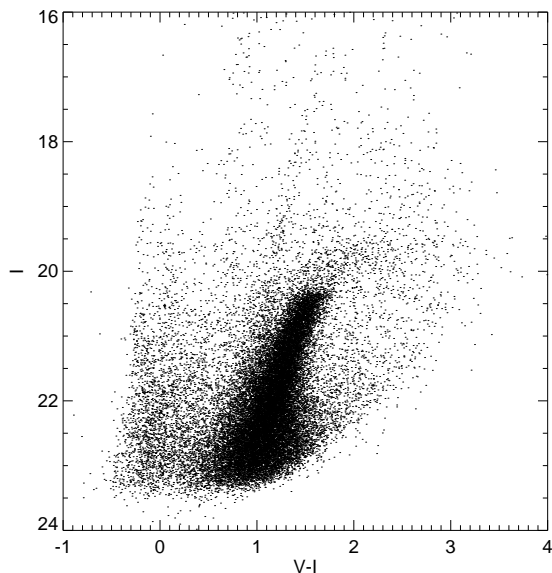


FIG. 1.— Color-magnitude diagram of IC1613. All the stars described in section 2 are plotted.

³ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

⁴ See the WFC User Notes at http://www.ing.iac.es/Astronomy/instruments/wfc/wfc_notes_apr98.html.

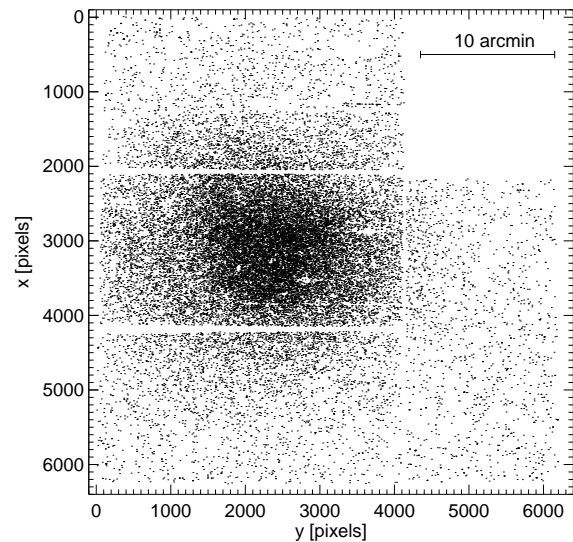


FIG. 2.— Distribution of resolved stars in IC1613. North is up and East to the left.

Udalsky (private communication). Several hundreds of stars were used for each chip, giving dispersions of the fits at the centers of mass of the point distributions of about 0.001. Calibration of chip 2, which was outside OGLE's field, was more laborious. In *V*, one standard star field observed during the IC1613 INT run was used to determine the transformations between chip 2 and chips 1 and 4. The dispersion of these transformations is ~ 0.005 . Then the transformation for the latter chips based on OGLE's photometry was used, bringing the chip 2 *V* photometry into the standard system. In *I*, chip 2 was calibrated differentially with respect to chip 4 using overlapping images obtained on the IAC80 telescope at Izaña, Tenerife, Spain, during a photometrical observing run. The dispersion at the center of mass is of the order of 0.01. Hence, the total error in our photometry is that given by Udalski et al. (2001), i.e., up to 0.02 for both *V* and *I* bands. Figure 1 shows our final (*V-I*, *I*) CMD⁵. The spatial distribution of these stars is presented in Fig. 2.

The errors given by ALLFRAME are the residuals of the PSF-fitting procedure, so they should be considered internal errors. Signal-to-noise limitations, stellar crowding, blending and starloss, which we can refer to as observational effects, are important error sources and significantly modify the CMD shape and stellar density distribution (Aparicio & Gallart 1995). To estimate the observational effects and the completeness of our photometry, we resorted to artificial stars tests. See Aparicio & Gallart (1995) for a detailed description of the procedure and the effects of crowding. Basically, a large number of artificial stars covering the same range in color and magnitude as the observed stars is added to the images using the corresponding PSF. These were placed on the images following a triangular grid in order to avoid crowding between artificial stars themselves and to optimally sample the chip fields. The photometry is then

⁵ The photometric data are available from the first author upon request.

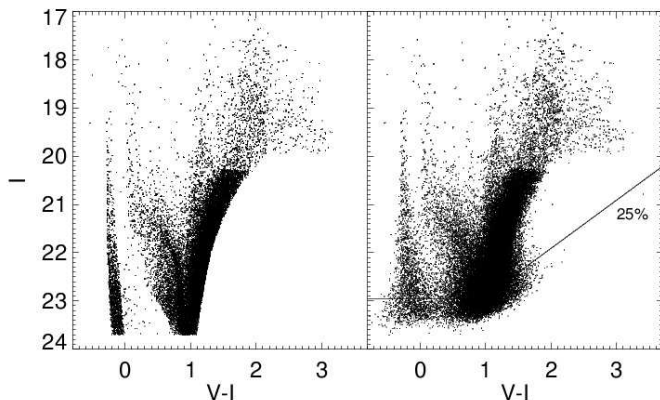


FIG. 3.— *Left*: Synthetic CMD produced by IAC-STAR showing the 153260 stars injected in chip 4 (see text for details). *Right*: CMD of the ~ 40000 artificial stars recovered both in V and I and considered to have good photometry as described in section 2. The line shows the 25% completeness limit as determined from the artificial star tests.

repeated in the exact same way as was done originally. A comparison of the input and output artificial-star list gives information about the completeness as a function of magnitude and galactocentric distance.

As the artificial star sample, we took a synthetic CMD produced by IAC-STAR⁶ (Aparicio & Gallart 2004) using the stellar evolution library of Bertelli et al. (1994) and the bolometric corrections of Castelli & Kurucz (2003). The SFR was chosen constant between 13 Gyr ago and now, while the metallicity range increases from 0.0008 to 0.002 at $t = 0$, to 0.0008 to 0.006 at the present time. These ranges were chosen wide enough so that they include the actual metallicity of IC1613. In total, 76630 artificial stars were added in 5 runs in each external chip, and twice as many in the central chip (#4) where crowding is more important. Figure 3 presents the injected and recovered CMDs for chip 4. The broken line indicates the 25% completeness limit, averaged over the galactocentric radius range, obtained from the ratio of recovered to injected stars as a function of magnitude. Figure 4 shows the completeness and error in recovered magnitude as a function of input magnitude for an inner and an outer field. It is important noticing that, even though the recovered artificial stars were filtered using the same values of σ , χ^2 and *SHARP* as the real stars, *external* errors can be as large as ~ 1 magnitude at the faint limit.

3. THE COLOR-MAGNITUDE DIAGRAM

The most evident feature of our CMD, Fig. 1, is the red giant branch (RGB), composed of low mass stars ($M \lesssim 1.8 - 2.0 M_{\odot}$; Chiosi et al. 1992) older than about 1 Gyr and burning hydrogen in a thin layer around an inert helium core. The age-metallicity degeneracy and the presence of the fainter extension of the asymptotic giant branch (AGB) in the same region of the CMD makes it difficult to get detailed information about the stars populating it. However, it is possible to place rough limits in time for given metallicities using theoretical isochrones. A more detailed determination of the chemical enrichment law (CEL) using this method, as well as its limita-

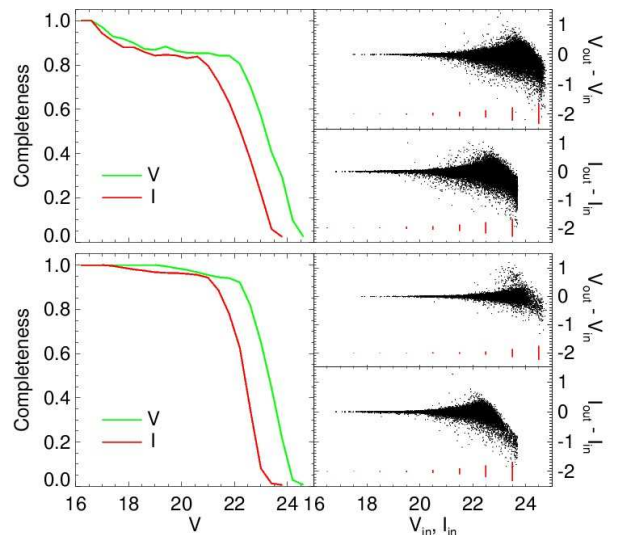


FIG. 4.— Completeness (*left*) and errors in recovered magnitudes (*right*) for a central field (chip 4, *top* panel), and an outer field (chip 1, *bottom* panel). The errorbars in the right panels show the dispersion per magnitude bin.

tions, is presented in section 5.1.

The presence of a well populated main sequence (MS) blueward of $V - I = 0$ and up to $I \sim 18.5$ indicates very recent star formation ($\lesssim 10$ Myr).

The stars with $0 \leq (V - I) \leq 0.6$ and $I \leq 22$ are most likely blue loop (BL) stars, highlighting the blue edge of the core He-burning loop, while the red edge (i.e., the red supergiant branch, RSG), although contaminated by foreground stars, is well defined from $(V - I) \sim 1.0$ to $(V - I) \sim 1.8$ and up to about $I \sim 16.5$. These are young and intermediate- to high-mass stars, so they are among the most metal-rich stars in IC1613. However, this is a poorly understood phase in stellar evolution and the theoretical models still contain large uncertainties owing to the importance of processes such as mass-loss, overshooting and rotation in very massive stars (see e.g., Maeder & Meynet 2001). The BL and RSG actually reach the red clump down to $I = 23.76$ (Cole et al. 1999), but the dispersion at the faint end of our CMD makes it impossible to distinguish them from the RGB stars below $I = 22$.

The final extension of the AGB, or red-tail (Gallart et al. 1994), extends horizontally redward from the RGB tip at $I \sim 20$. AGBs are shell H- and He-burning stars, of low and intermediate mass and age over about 0.1 Gyr. Their relatively large number indicates a possibly important intermediate-age population with relatively high metallicity, which would be compatible with the enhanced SFR between 3 to 6 Gyrs ago found by S03.

Because of the wide field of view, the diagram also contains a relatively large number of foreground stars. Most stars with $0.5 \leq V - I \leq 1.2$ and $I \leq 20$ are probably Galactic dwarfs since their number is the same for the middle and bottom panels in Fig. 5 after correcting for the difference in area. More generally, the foreground contamination is rather important for $V - I \gtrsim 0.6$.

Although old stars ($\gtrsim 10$ Gyr) are very likely present in the RGB, our CMD is not deep enough to detail the

⁶ The code, available for free use, can be executed at the IAC-STAR website <http://iac-star.iac.es/>.

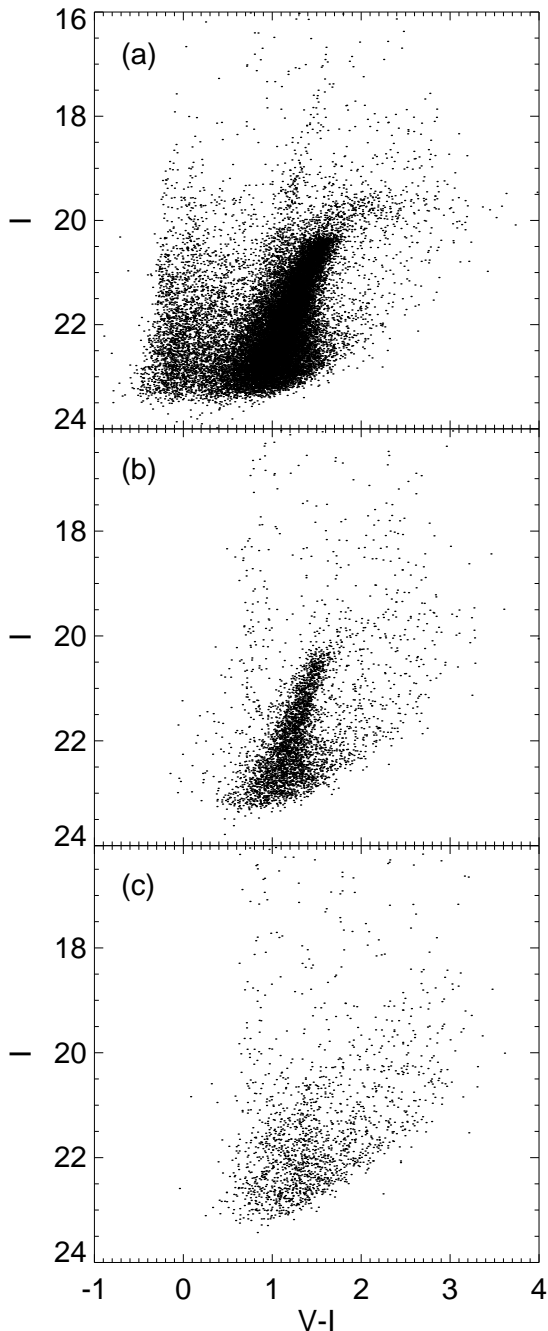


FIG. 5.— Color-magnitude diagram of IC1613 for different galactocentric distances. The radius ranges are (a) $r \leq 10'$, (b) $10' < r \leq 16'.5$, (c) $r > 16'.5$.

old, low metallicity population as it would if fainter MS stars were observed. The existence of a *bona fide* old population in IC1613 is known thanks to the presence of RR Lyrae stars (Saha et al. 1992; Dolphin et al. 2001) and CMDs from Hubble Space Telescope observations showing core helium burning, horizontal branch stars (Cole et al. 1999; Dolphin et al. 2001; S03) and the oldest MS turnoffs (Gallart 2007).

4. MORPHOLOGY, SPATIAL EXTENT & DISTRIBUTION OF STELLAR POPULATIONS

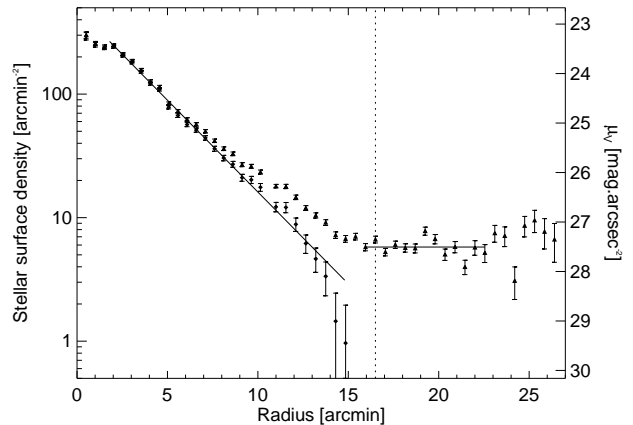


FIG. 6.— Number density of stars as a function of galactocentric distance before (*triangles*) and after (*diamonds*) background subtraction. The right-hand vertical axis gives a rough estimate of the surface magnitude, calibrated as described in text. The horizontal line is the weighted mean density of ellipses 29 to 41, which has been adopted as the background level. The exponential fit has a scale length of $2'.9 \pm 0.1$. The vertical dotted line shows where the foreground stars start to dominate, as obtained from the CMDs (see section 4).

To characterize the morphology of IC1613, we plotted the RGB star distribution obtained from our photometry, and convolved the resulting map with a Gaussian of $\sigma = 50''$ using IRAF's GAUSS from the IMFILTER package. The result of this process is a smooth map of the stellar density highlighting the morphology of the galaxy. Fitting ellipses to the isodensity contours was done with IRAF's ISOPHOTE routine.

From the best fitted ellipses, where the crowding is low but the star number sufficient, we find a position angle of 80° and an eccentricity $\epsilon = 1 - b/a = 0.15$, in good agreement with the values given by Ables ($PA = 81^\circ$, $\epsilon = 0.18$; 1972). Following the shape of the isopleths, we divided the galaxy into concentric ellipses at small radii ($\lesssim 10'.5$) and circles at larger ones that we used for radial star counts and stellar populations gradient analysis. Their semi-major axis increases in steps of 100 pixels, corresponding to $33''$.

Figure 6 shows the radial profile of the galaxy constructed from the number of stars in each ellipse after correcting for completeness. The correction was obtained from the ratio of the number of recovered to injected stars in the artificial star test for each annular region. The area of the ellipses has been calculated via Monte-Carlo sampling, carefully taking into account the gaps between the chips as well as the regions around saturated stars when calculating the effective surface. An approximate surface brightness scale, shown on the right-hand side of Fig. 6, was calculated from the stellar density in each ellipse. The calibration was calculated by comparing the star number with the total, sky subtracted flux for each ellipse then averaged over the radius range for consistency. An exponential least square fit to this curve between $2'$ and $15'$ from the center gives a scale length of $2'.9 \pm 0.1$ (620 ± 20 pc) and central surface brightness $\mu_{V,0} = 22.7 \pm 0.6$. The former value is slightly smaller than the 760 ± 50 pc ($\sim 3'.5 \pm 0.2$) given by Hodge et al. (1991). However, a similar larger length is obtained when fitting only the inner $\sim 7'$, as was done by the authors because of the limited depth of their photometry, and

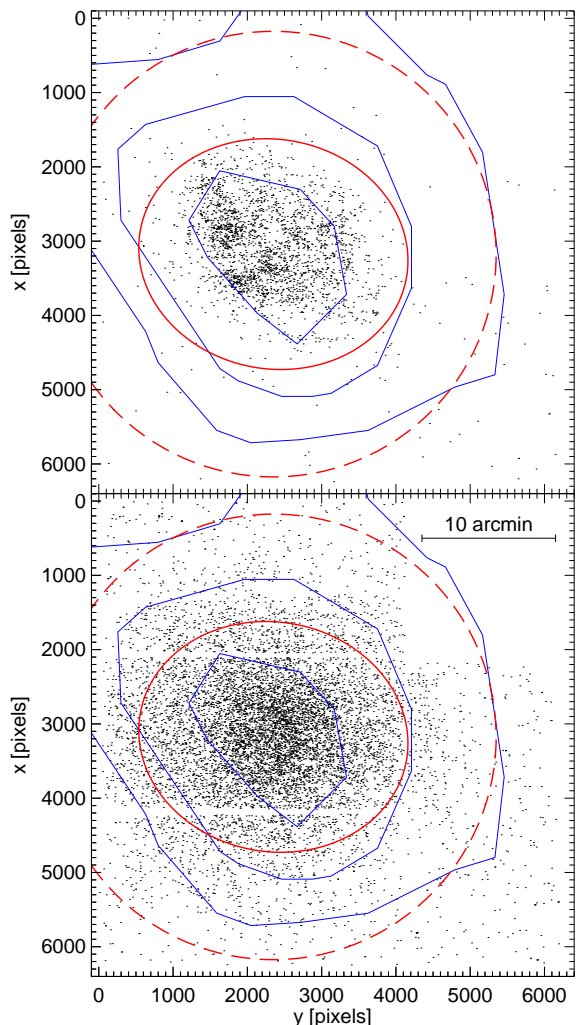


FIG. 7.— Spatial distribution of young (MS+BL+RSG; *top*) and older (AGB+RGB; *bottom*) stars. The red ellipse shows the extent of the MS stars ($r=10'$). The red dashed circle indicates where the foreground stars start to dominate ($r=16.5'$). The neutral hydrogen emission contours (0.2 , 6.2 and $14.2 \text{ Jy km s}^{-1}$) from Hoffman et al. (1996) have been overplotted in blue (*see text for details*).

omitting the crowding correction. The profile seems to get steeper at $r \sim 12'$, but this change of slope could be an artifact of the background subtraction and small number statistics.

The large field of view covered by the WFC permits to study the spatial gradients of the stellar population across the galaxy. Ideally, that would give us hints on its formation and evolution. However, in the case of shallow CMDs, the spatial variations of the morphology of the CMD only reflect accurately differences in the SFH over the last several hundred million years. Such variations have been observed in all the known dwarf irregular galaxies through CMD morphology (e.g., WLM: Minniti & Zijlstra 1996; NGC

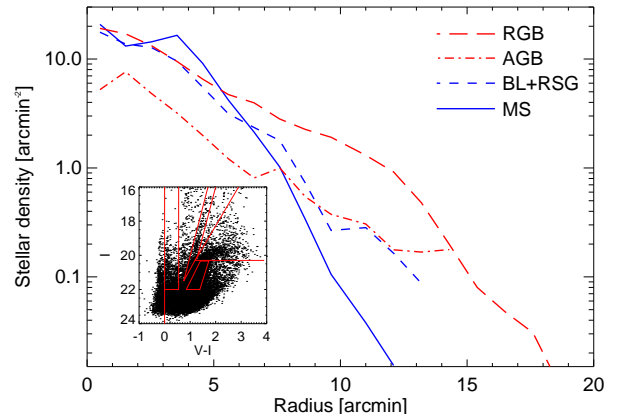


FIG. 8.— Stellar densities of the different populations of resolved stars after correction for completeness and background contamination. The stars selected for each population are shown in the inset. The RGB profile was divided by four to fit on the graph. The errorbars have been omitted for clarity. Note the difference in the scale length of the older (RGB, AGB) and younger (MS, BL+RSG) populations (*see text for details*).

6822: Battinelli et al. 2006; Leo A: Vansevičius et al. 2004; Phoenix: Martínez-Delgado et al. 1999) or distribution of the variable star populations (e.g., in Phoenix: Gallart et al. 2004; in Leo I: Baldacci et al. 2004).

Figure 5 shows that it is also the case for IC1613 and confirms the difference in relative number of young and old stars found by S03 between their outer HST field and a central field studied earlier by Cole et al. (1999). We divided the galaxy into three regions following the morphology of the CMD of each individual ellipse defined above: the inner part of the galaxy where stars younger than about 500 Myr are present ($r \leq 10.1'$, Fig. 5a), the region at intermediate distance with no young star but still a well defined RGB ($10.1' < r \leq 16.5'$, Fig. 5b), and the outermost part of our observed field, dominated by foreground stars ($r > 16.5'$, Fig. 5c). The corresponding spatial limits, as well as the HI contours from Hoffman et al. (1996), are displayed over the stellar distribution of the young and old populations in Fig. 7. Note that the HI contours were shifted by -0.6 ($+100$ pixels in y) and 2.9 (-500 pixels in x) in right ascension and declination, respectively. This corresponds to the offset between the astrometry of Lake & Skillman (1989) and Hoffman et al. (1996), and adopting the former for the HI contours correctly places the HII regions of Hodge et al. (1990) on top of the star forming regions, and fits our star distribution better. Although the RGB of Fig. 5c is not clearly defined, a substantial fraction of the displayed stars probably belong to IC1613. This corroborates the results of Albert et al. (2000), who found carbon stars extending up to $15'$ from the center of the galaxy, and shows that IC1613 is actually more extended than previously thought.

To give a quantitative measure of the gradient in the age composition of the stars in IC1613, the stellar surface density for different populations of resolved stars is presented in Fig. 8. The age gradient is clearly visible: while the density of the older stars follows the expected exponential decrease from the central region, that of the young population peaks at a radius of $\sim 3'$ and vanishes rapidly as the radius increases. This results in the scale

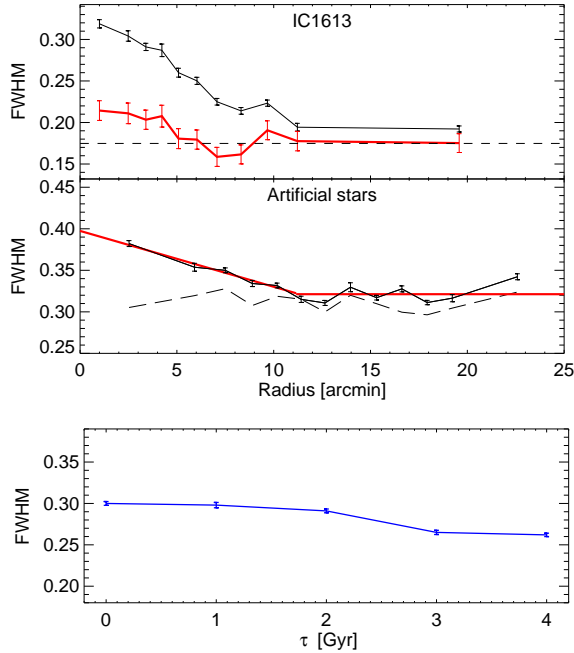


FIG. 9.— *Top*: Width of the RGB of IC1613 at $M_I = -3.5$ as a function of galactocentric distance, before (*thin line*) and after (*thick red line*) correction for the effects of crowding. The dashed line indicates the mean value of the corrected width beyond $\sim 5'$. *Middle*: Width of the injected (*long-dashed line*) and recovered (*full thin line*) RGB of the artificial stars tests. The thick red line is a fit to the recovered width. *Bottom*: Width of an artificial RGB as a function of the age of the youngest stars in the CMD. The small change between $\tau = 0$ and 1 Gyr is probably due to the presence of stars from the RSG sequence. In all cases the errorbars correspond to the dispersion of twenty solutions. The vertical scale is the same on all three panels.

length of the young population being much smaller than that of the older stars: a fit to the profiles between $3'5$ and $12'1$ from the center of IC1613 gives scale lengths of $1'19 \pm 0.04$, $2'0 \pm 0.1$, $3'2 \pm 0.2$ and $3'8 \pm 0.1$ for the MS, BL+RSG, AGB and RGB, respectively. The off-centered peak in the distribution of the young population, visible at $r \sim 3' - 3'5$ in Fig. 8, is due to the fact that the star forming regions are distributed in a somewhat circular pattern at this distance from the center (Hodge et al. 1990), where Silich et al. (2006) observed a higher H I column-density.

Because of the large dependence of the RGB color on metallicity, the position of the RGB in a CMD can be used to estimate the metallicity of the stellar system using empirical relations (e.g., Da Costa & Armandroff 1990). For the same reason, the width of the RGB is often considered to be an indication of the metallicity dispersion. On the CMDs presented in Fig. 5, it appears that the RGB in the central region is wider than that at larger radii and suggests the existence of a metallicity gradient. However, a RGB width gradient may also reflect an observational-effects gradient. To check this possibility, the following procedure was used, including measurements of real- and artificial-star RGB width and error estimates. We measured the width of the RGB at $M_I = -3.5$ as a function of galactocentric distance for the real stars as follows: for each radius interval, chosen so that the RGB contains about 800 stars, a sub-

sample of 450 RGB stars was selected at random. The resulting RGB was sliced in intervals of 0.25 magnitude between $20.5 \leq I \leq 22$, and the width of the RGB in each magnitude range was obtained from the full-width at half-maximum (FWHM) of a Gaussian fit to the color function (CF). The width at $M_I = -3.5$ was then interpolated from a linear fit to the FWHM versus magnitude plot. We repeated this operation twenty times using a different subsample of RGB stars each time, and used the dispersion of these solutions as the errorbars. The same process was followed for the synthetic CMD used in the artificial stars tests, except that the radius bins and random subsamples contained 2500 and 1500 stars, respectively. The resulting plot is presented in Fig. 9 for IC1613 (*top*) and the artificial stars (*middle panel*).

It shows that the RGB recovered in the artificial star tests is wider in the center of the galaxy. In addition to the expected FWHM widening due to signal-to-noise limitations, crowding in the central part further disperses the stars on the CMD. Crowding is important and affects the width of the RGB up to $r \sim 10'$. To correct the observed RGB for the effects of crowding, we calculated the broadening parameter as a function of radius by subtracting in quadrature the injected width from the recovered one. The corrected width was then obtained by subtracting in quadrature the broadening parameter from the observed RGB width, and is shown as the thick red line in the upper panel of Fig. 9. The FWHM of the corrected RGB still presents a significant variation across the central $\sim 6'$. A higher metallicity dispersion in the central region could be responsible for this residual width excess. However, the lower panel of Fig. 9, showing the width of artificial RGBs for which the age of the youngest stars is progressively older, indicates that this excess is consistent with the presence of stars between 1 and 3–4 Gyr old in the center. Thus, there is no strong evidence of a metallicity gradient across the galaxy but its presence cannot be ruled out with the present set of data.

5. RECENT STAR FORMATION HISTORY

5.1. The Method

The reconstruction of the recent SFH has been performed in a way similar to that described in Hidalgo & Aparicio (2007, in preparation) or Gallart et al. (1999). The main difference here resides in the fact that our CMD is not sufficiently deep to contain discriminating information about intermediate-age and old stars. We limited our study to the recent SFH, i.e., the last ~ 300 Myr, based on the MS, BL and RSG populations. It thus limited the determination of the SFH to the inner $r \lesssim 10'$ since these populations are absent beyond this radius.

In short, the SFH is derived from the comparison of the star distribution of the observed CMD with that of a synthetic CMD. The synthetic CMD to be used in the comparison needs to cover a range of age and metallicity at least as large as the one that can be expected in such a dwarf irregular galaxy. It was generated by IAC-STAR (Aparicio & Gallart 2004) using the stellar evolution library of Bertelli et al. (1994) and the bolometric corrections from Castelli & Kurucz (2003), with the following parameters: the SFR was chosen constant between 13 Gyr ago and now, the initial mass function

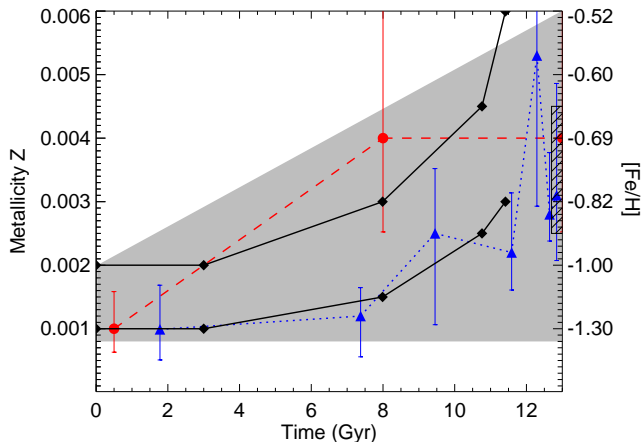


FIG. 10.— CEL of IC1613. The diamonds indicate, for a given age, the minimum and maximum values found by fitting theoretical isochrones from the library of Padua (Girardi et al. 2002) to the upper RGB. For reference, the CELs obtained via the ‘Tolstoy’ and ‘Dolphin methods’ from S03 are shown as red circles and blue triangles, respectively. The grayed region is the CEL used for the comparison CMD in the SFH analysis. The striped region in the last 300 Myr shows the metallicity range that gave the lowest χ^2 when determining the SFH. The right-hand scale was converted from the abundance by mass assuming $Z_{\odot} = 0.0198$.

(IMF) was that of Kroupa et al. (1993), and the fraction of binaries was set to zero. To fix the input CEL we fitted isochrones of different metallicities to the upper RGB of the outer field where crowding is not dominant. We used the Girardi et al. (2002) isochrones for different ages (1.585, 2.239, 5.012, 10.00 and 12.59 Gyr old) and metallicities between $Z = 0.0005$ and $Z = 0.006$ in steps of 0.0005. The metallicities that are not available in the original library were interpolated using IAC-STAR. A metallicity was considered valid at a given age if the corresponding isochrone was inside the FWHM of the RGB between $20.4 \leq I \leq 21$. Figure 10 (*filled diamonds*) shows the values obtained through this method. Although the method is rather simplistic, our resulting CEL is in very good agreement with those derived by S03. However, Gallart et al. (2005) showed that the theoretical isochrones are generally too vertical with respect to the empirical ones, leading to a slight overestimation of the metallicity. The grayed region represents the metallicity range employed to create the comparison CMD. It is mainly used for producing the RGB, from which we obtain the mean SFR between 1500 and 13000 Myr, and serves a normalization purpose for the young SFH. For the stars younger than 300 Myr, we tried to put constraints on their metallicity by further restricting the metallicity range in the comparison CMD to intervals of 0.002 in abundance by mass, and ran the algorithm three times with the following ranges: $Z = 0.0015$ -0.0035, $Z = 0.0025$ -0.0045 and $Z = 0.0035$ -0.0055.

In order to simulate the observational effects and allow a more realistic comparison with the real CMD, we applied the dispersion in color and magnitude of the synthetic stars recovered from the crowding tests to the comparison CMD, following the same procedure as in Gallart et al. (1999).

In the observed and comparison CMDs, the MS, BL and RSG sequence are then divided into ‘boxes’. Because the box selection could influence the resulting SFH, we

used three different types of box to rule out this possibility: two regular grids with large (0.3 and 0.5 in color and magnitude, respectively) and small (0.2 and 0.3) box size, and an “à la carte” parametrization. In the latter, the size and shape of the boxes are chosen taking into account the knowledge and model limitations of the evolutionary phases, in particular the slope of the RSG sequence and the position of the BL. The regular grids were also shifted in color and magnitude to check for consistency and ensure the significance of the result.

Additionally, the synthetic stars are divided into partial models, each with a small range in age. The temporal resolution is limited by the quantity of information contained in the CMD, which depends on the quality of the data. It was chosen by comparing the capacity of the algorithm to recover the known SFH of a synthetic CMD, after the observational effects had been simulated as described above, using different time ranges. Above a certain time resolution—which depends on age—the recovered SFH was mainly made of short, violent bursts of star formation separated by periods of inactivity, regardless of the input SFH (see also Aparicio & Hidalgo 2007).

The reconstructed SFH is a linear combination of the different partial models. The best solution is obtained through χ^2 -minimization by a genetic code. A thorough description of the algorithm and method is presented in Aparicio & Hidalgo (2007). In total, we used 24 models with different CMD parametrization and time resolution. The consistency of the method was checked by solving the SFH of synthetic CMDs and comparing the solutions with the input SFHs. Some of the regular grid models did not give a satisfactory solution, but the discrepancies could generally be traced to small differences in the location of evolutionary phases in the CMD, while the solutions obtained with the *à la carte* parametrization were found to be more stable and are the ones we will present here.

5.2. The Results

Of the three metallicity ranges used for the stars younger than 300 Myr, the second one, i.e., $Z = 0.0025$ -0.0045, gave the best solutions, and is shown as a striped region in Fig. 10. This is consistent with the H II region metallicity of Talent (1980). Our best solutions for the SFHs at different galactocentric distances are presented in Fig. 11. The radius ranges were chosen so that the CMDs contain the same number of stars. The error bars correspond to the dispersion of twenty solutions for which $\chi^2 = \chi_{best}^2 + 1$ (see Aparicio & Hidalgo 2007).

The overall picture is a relatively constant SFR at all radii, decreasing with increasing radius, while the mean age of the stars increases with radius. The very central region, panel (a), shows a fairly constant SFR for the last 300 Myr of $(1.6 \pm 0.8) \times 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$, in excellent agreement with the value found by Cole et al. ($1.6 \times 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$; 1999) using the V-band luminosity function of their WFPC2 central field and assuming a Salpeter IMF. The sharp drop in the last ~ 25 Myr is in agreement with the lack of very bright stars at the center of IC1613 first noted by Hodge et al. (1991).

Between 2’5 and $\sim 6'$ [(b)-(d)] the SFR increased by a factor ~ 2 -3 in the last 100-150 Myr. This corresponds

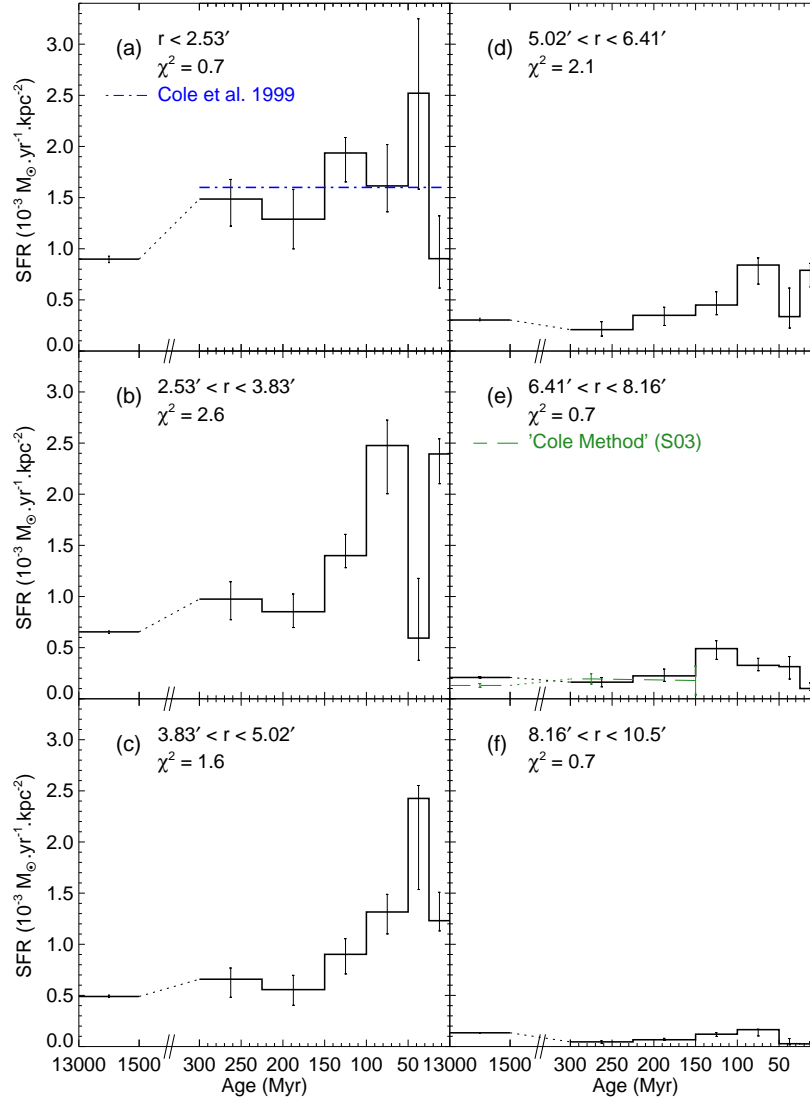


FIG. 11.— Best SFR(t) obtained for each galactocentric distance. The radial ranges were chosen so that the corresponding CMDs contain the same number of stars. The error bars correspond to the dispersion of twenty solutions for which $\chi^2_{\sigma} = \chi^2 + 1$, where χ^2 is the residual of the best solution, indicated in each panel. The gap in the solutions between 300 and ~ 1500 Myr is due to the lack of information from either the young populations or the RGB in this age range. The solutions obtained by Cole et al. (1999) and Skillman et al. (2003) for their respective WFPC2 field are plotted in panels (a) and (e).

to the peak in the radial distribution of young stars and H II regions found by Hodge et al. (1990).

The field studied by S03 is a small fraction of the region for which the SFH is represented in panel (e). The SFH calculated via the ‘Cole method’⁷ in S03, shown as the green long-dashed lines, is very similar to the one we obtained here for the whole elliptical annulus. At larger

radii, the number of stars formed more recently than about 300 Myr decreases to a negligible value when the radius reaches $\sim 10'$.

6. CONCLUSIONS

We have presented an analysis of the stellar content, morphology, and recent star formation history of the Local Group dIrr galaxy IC1613 based on wide-field ($V-I,I$) photometry of resolved stars.

The distribution of resolved stars can be fitted with ellipses of position angle 80° and eccentricity 0.15. The exponential fit of the resulting radial profile has a scale length of 2.9 ± 0.1 . The relatively large number of RGB

⁷ Three methods were used in S03 to calculate the SFH: the ‘Dolphin method’ gives the SFR on a relative scale only. For the ‘Tolstoy method’, the vertical scale of their Fig. 7 gives a mean SFR $\sim 3 \times 10^{-3} M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$, a factor ~ 15 – 20 higher than that of the ‘Cole method’ and as high as the mean value of the SFR over the whole galaxy (Mateo 1998).

stars still present in the outer part of our observed field ($r > 16''.5$) indicates that the galaxy is actually more extended than previously estimated.

The well-populated young evolutionary phases of the CMD of the central region of IC1613 indicate very recent star formation ($\lesssim 10$ Myr). The changing CMDs as a function of galactocentric distance show a strong gradient in the age of the younger stellar population, with the young stars lying preferentially in the central part, while the older ones are distributed more uniformly. No evidence of star formation more recent than about 300 Myr was detected beyond $r \gtrsim 10''$.

Analysis of the width of the RGB as a function of radius is consistent with no metallicity gradient. The combination of crowding effect and the presence of younger stars in the RGB is responsible for the widening toward the center of the galaxy.

In the region where the recent SFH could be studied ($r \lesssim 10''$), the results indicate a decreasing SFR(t) from

the center outward as expected from the distribution of neutral gas in IC1613, with the exception of the annular region where the star forming regions are clustered ($r \sim 4''$) and therefore the SFR is a factor ~ 2 -3 higher.

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REFERENCES

- Ables, H. D. 1972, Publications of the U.S. Naval Observatory Second Series, 20, 1
- Albert, L., Demers, S., & Kunkel, W. E. 2000, *AJ*, 119, 2780
- Aparicio, A., & Gallart, C. 1995, *AJ*, 110, 2105
- Aparicio, A., & Gallart, C. 2004, *AJ*, 128, 1465
- Aparicio, A., & Hidalgo, S. L. 2007, *AJ*, submitted
- Battinelli, P., Demers, S., & Kunkel, W. E. 2006, *A&A*, 451, 99
- Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F., & Nasi, E. 1994, *A&AS*, 106, 275
- Borisova, J., Kurtev, R., Georgiev, L., & Rosado, M. 2004, *A&A*, 413, 889
- Baldacci, L., Matonti, F., Rizzi, L., Clementini, G., Held, E. V., Momany, Y., Di Fabrizio, L., & Saviane, I. 2004, *Memorie della Societa Astronomica Italiana*, 75, 126
- Castelli, F., & Kurucz, R. L. 2003, *IAU Symposium*, 210, 20P
- Chiosi, C., Bertelli, G., & Bressan, A. 1992, *ARA&A*, 30, 235
- Cole, A. A., et al. 1999, *AJ*, 118, 1657
- Da Costa, G. S., & Armandroff, T. E. 1990, *AJ*, 100, 162
- Dolphin, A. E., et al. 2001, *ApJ*, 550, 554
- Gallart, C., Aparicio, A., Chiosi, C., Bertelli, G., & Vilchez, J. M. 1994, *ApJ*, 425, L9
- Gallart, C., Freedman, W. L., Aparicio, A., Bertelli, G., & Chiosi, C. 1999, *AJ*, 118, 2245
- Gallart, C., Stetson, P. B., Hardy, E., Pont, F., & Zinn, R. 2004, *ApJ*, 614, L109
- Gallart, C., Zoccali, M., & Aparicio, A. 2005, *ARA&A*, 43, 387
- Gallart, C. 2007, in *IAU Symp. 241, Stellar Populations as Building Blocks of Galaxies*, ed. A. Vazdekis & R. Peletier (Cambridge: Cambridge Univ. Press), in press
- Girardi, L., Bertelli, G., Bressan, A., Chiosi, C., Groenewegen, M. A. T., Marigo, P., Salasnich, B., & Weiss, A. 2002, *A&A*, 391, 195
- Hodge, P., Lee, M. G., & Gurwell, M. 1990, *PASP*, 102, 1245
- Hodge, P. W., Smith, T. R., Eskridge, P. B., MacGillivray, H. T., & Beard, S. M. 1991, *ApJ*, 369, 372
- Hoffman, G. L., Salpeter, E. E., Farhat, B., Roos, T., Williams, H., & Helou, G. 1996, *ApJS*, 105, 269
- Kroupa, P., Tout, C. A., & Gilmore, G. 1993, *MNRAS*, 262, 545
- Lake, G. R., & Skillman, E. D. 1989, *AJ*, 98, 1274
- Lee, H., Grebel, E. K., & Hodge, P. W. 2003, *A&A*, 401, 141
- Lee, M. G., Freedman, W. L., & Madore, B. F. 1993, *ApJ*, 417, 553
- Lozinskaya, T. A., Moiseev, A. V., & Podorvanyuk, N. Y. 2003, *Revista Mexicana de Astronomia y Astrofisica Conference Series*, 15, 284
- Maeder, A., & Meynet, G. 2001, *A&A*, 373, 555
- Magrini, L., et al. 2005, *MNRAS*, 361, 517
- Martínez-Delgado, D., Gallart, C., & Aparicio, A. 1999, *AJ*, 118, 862
- Mateo, M. L. 1998, *ARA&A*, 36, 435
- Minniti, D., & Zijlstra, A. A. 1996, *ApJ*, 467, L13
- Pietrzyński, G., Gieren, W., Soszyński, I., Bresolin, F., Kudritzki, R.-P., Dall'Ora, M., Storm, J., & Bono, G. 2006, *ApJ*, 642, 216
- Saha, A., Freedman, W. L., Hoessel, J. G., & Mossman, A. E. 1992, *AJ*, 104, 1072
- Silich, S., Lozinskaya, T., Moiseev, A., Podorvanuk, N., Rosado, M., Borisova, J., & Valdez-Gutierrez, M. 2006, *A&A*, 448, 123
- Skillman, E. D., Kennicutt, R. C., & Hodge, P. W. 1989, *ApJ*, 347, 875
- Skillman, E. D., Tolstoy, E., Cole, A. A., Dolphin, A. E., Saha, A., Gallagher, J. S., Dohm-Palmer, R. C., & Mateo, M. 2003, *ApJ*, 596, 253
- Stetson, P. B. 1987, *PASP*, 99, 191
- Stetson, P. B. 1994, *PASP*, 106, 250
- Talent, D. L. 1980, Ph.D. Thesis
- Udalski, A., Wyrzykowski, L., Pietrzyński, G., Szewczyk, O., Szymański, M., Kubiak, M., Soszyński, I., & Żebruń, K. 2001, *Acta Astronomica*, 51, 221
- van den Bergh, S. 2000, *The galaxies of the Local Group* (Cambridge, UK: Cambridge University Press)
- Vansevicius, V., et al. 2004, *ApJ*, 611, L93